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Nussbaumer, Samuel U ; Zemp, Michael ; Jansson, Peter

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Summary report on the “Workshop on Measurement and Uncertainty Assessment of Glacier Mass Balance”

9–11 July 2012, Tarfala, Sweden

Edited by:

Samuel Nussbaumer, World Glacier Monitoring Service, Department of Geography, University of Zurich, Switzerland

Michael Zemp, World Glacier Monitoring Service, Department of Geography, University of Zurich, Switzerland

Peter Jansson, Department of Physical Geography and Quaternary Geology, Stockholm University, Sweden



Photo: Rafael Jensen, 11 July 2012

Executive summary

From 9–11 July 2012 the World Glacier Monitoring Service (WGMS) organized in collaboration with Stockholm University a workshop on measurement and uncertainty assessment of glacier mass balance. The workshop built on the results and experience of earlier workshops in Tarfala in 1998 (Fountain et al. 1999) and Skeikampen in 2008 (Annals of Glaciology 50(50), 2009), with focus on the re-analysis of glacier mass balances including a (standardized) uncertainty assessment. The meeting was held at the Stockholm University, Tarfala Research Station, in northern Sweden, and brought together 17 representatives of the leading research groups currently working on these issues.

The major aims of the workshop were to discuss methods and to identify and quantify related uncertainties of mass balance measurements from the ground, air and space, as well as to provide best practices for the homogenization, validation and re-calibration of (long-term) observational series (re-analysis of glaciological and geodetic mass balance series).

These goals are based on the following research questions:

- Which are sources of potential errors of glacier mass balance measurements, and how are these potential errors considered by glaciological and geodetic methods?
- How can the related uncertainties be quantified?
- What are typical values (ranges) for the systematic and stochastic uncertainties?
- What are the consequences for the comparison of glaciological and geodetic mass balances?
- What are related consequences for the interpretation of glacier mass balance results as indicators of climate change, fresh water resources, and contributors to sea level change?

The workshop included key note presentations as input for the subsequent discussions on how to tackle the issues mentioned above. These covered uncertainties and problems related to the direct glaciological method, re-analysis of long-term mass balance series and homogenization methods, and co-registration and bias correction of elevation data. Newly available techniques such as airborne laser-scanning as well as statistical tools to assess the quality of mass balance series were discussed, too. As final outcome of the workshop, a joint publication in a peer-reviewed journal is in preparation and will be made available as soon as ready. It includes a review based on the expertise of the workshop participants working with long-term monitoring mass balance programmes, supplemented with recommendations. The corresponding paper draft and the publication strategy were discussed during the meeting, and the final publication is planned to be submitted by the beginning of 2013.

The setting of the venue greatly supported the spirit of intensive and constructive discussions during the two workshop days and the excursion day to the renowned and best-investigated Storglaciären, with its long-term monitoring mass balance series.

The workshop was “A Marcus Wallenberg Symposium” sponsored by the Marcus Wallenberg Foundation for International Cooperation in Science and co-sponsored by the International Union of Geology and Geophysics (IUGG) through the International Association of Cryospheric Sciences (IACS) as well as by the International Glaciological Society (IGS). Additional financial support came from the WGMS which receives substantial funds from the Swiss GCOS Office at the Federal Office of Meteorology and Climatology MeteoSwiss, and the Department of Geography of the University of Zurich, Switzerland.

Background

Changes in glacier mass are key element of glacier monitoring, providing important information for assessing climatic changes, water resources, and sea level changes (Kaser et al. 2006; Zemp et al. 2009). The available dataset of in-situ glacier mass balance measurements covers the past six decades (WGMS 2008). The majority of these data series consists of just a few observation years and most results are reported without quantitative error bars. However, there are a dozen mass balance programmes with continuous observations dating back to 1960 or earlier (Zemp et al. 2009). Combined with decadal geodetic surveys, these long-term measurement series provide a unique opportunity for a re-analysis of the mass balance series and a quantitative assessment of related uncertainties (e.g. Andreassen et al. 2012, Cogley 2009, Escher-Vetter et al. 2009, Fischer 2010, 2011, Huss et al. 2009, Koblet et al. 2010, Nuth and Kääb 2011, Rolstad et al. 2009, Thibert et al. 2008, Zemp et al. 2010).

Since this beginning of internationally coordinated systematic observations on glacier variations in 1894, a valuable and increasingly important data basis on glacier changes has been built up. In 1986 the WGMS started to maintain and continue the collection of information on ongoing glacier changes, when the two former International Commission on Snow and Ice (ICSI) services PSFG (Permanent Service on Fluctuations of Glaciers) and TTS/WGI (Temporal Technical Secretary/World Glacier Inventory) were combined. As a contribution to the Global Environment Monitoring System (GEMS/GTOS) of the United Nations Environment Programme (UNEP) and to the International Hydrological Programme (IHP) of the United Nations Educational, Scientific and Cultural Organization (UNESCO), the WGMS of the International Association of Cryospheric Sciences (IACS) and the World Data System of the International Council for Science (WDS/ICSU) today collects and publishes worldwide standardized glacier data.

Venue and participants

The workshop was held at Tarfala Research Station (northern Sweden). The station is located in a sub-Arctic alpine environment in the Tarfala valley (67°55' N; 18°36' E) at 1130 m a.s.l. in the Kebnekaise Mountains, Swedish Lapland. The valley is surrounded by glaciers and peaks up to 2000 m a.s.l. The research station can be reached by foot (25 km hike) or by helicopter from the nearest village, Nikkaluokta. Public transportation is available to Nikkaluokta (bus from Kiruna airport and train station).

Tarfala Research Station is run by the Department of Physical Geography and Quaternary Geology, Stockholm University. The station, and its activities, was founded in 1946 when measurements of mass balance were started on Storglaciären, c. 1 km from the station. These measurements now constitute the world's longest detailed mass balance record. Storglaciären is also one of the most well-documented glaciers in the world. Tarfala staff has been instrumental in producing publications on mass balance measurements (e.g. Kaser et al. 2003) and more recently to update and improve the international Glossary on mass balance terminology (Cogley et al. 2011). The methods of mass balance measurements have to a large extent been developed on Storglaciären over the years and Tarfala has also hosted the earlier workshop mentioned above on mass balance measurements in 1998 (Fountain et al. 1999). The station is fully modern with running water and electric power despite being 25 km from the nearest road. The station was expanded in 2003 with a new lecture or

conference room through a generous donation from the Wallenberg Foundation. With this addition Tarfala has become an excellent site for both teaching and conferences concerning the alpine environment.

The workshop was attended by 17 experts currently performing and analysing mass balance measurements by means of glaciological and geodetic methods:

Liss Andreassen, Norwegian Water Resources and Energy Directorate (NVE), Norway: measurement and modelling of Norwegian glaciers, laser-scanning and remote sensing techniques at Langfjordjøkelen, northern Norway.

Hallgeir Elvehøy, Norwegian Water Resources and Energy Directorate (NVE), Norway: Norwegian glacier monitoring, with focus on Engabreen and Nigardsbreen.

Heidi Escher-Vetter, Kommission für Erdmessung und Glaziologie (KEG), Abt. Glaziologie, Bayerische Akademie der Wissenschaften, Germany: long-term mass balance measurements on Vernagtferner, Austria, interpolation methods and influence of density assumptions.

Andrea Fischer, Institute of Mountain Research: Man and Environment, Austrian Academy of Sciences, and Institute of Meteorology and Geophysics (IMGI), University of Innsbruck, Austria: direct and geodetic mass balances on Hintereisferner, Austria, and homogenization of the data series.

Matthias Huss, Department of Geosciences, University of Fribourg, Switzerland: mass balance of Alpine glaciers and re-analysis and homogenization of data series.

Bernhard Hynke, Zentralanstalt für Meteorologie und Geodynamik (ZAMG), Austria: direct glaciological and laser-scanning measurements at Wurtenkees and Goldbergkees, Austria, re-analysis of data series.

Philip Joerg, Department of Geography, University of Zurich (UZH), Switzerland: airborne laser-scanning for operational glacier monitoring, Findelengletscher, Switzerland.

Geir Moholdt, Scripps Institution of Oceanography, University of California, San Diego, USA: remote sensing and mass balance of (Canadian) Arctic glaciers (including modelling), within the projects ICESat and GRACE.

Christopher Nuth, Department of Geosciences, University of Oslo (UiO), Norway: satellite remote sensing and geodetic glacier changes, co-registration of digital elevation models.

Cecilie Rolstad Denby, Norwegian University of Life Sciences (UMB), Norway: geodetic glacier mass balance and its uncertainty, Svartisen ice cap, Norway.

Dorothea Stumm, International Centre for Integrated Mountain Development (ICIMOD), Nepal: mass balance programmes of glaciers in the Himalayas (Yala, Langtang), New Zealand (Brewster) and Antarctica, capacity building.

Emmanuel Thibert, Institut de recherche en sciences et technologies pour l'environnement et l'agriculture (Irstea), France: analysis and re-analysis of glacier mass balance and related error estimation by means of statistics at Glacier de Sarennes, France.

Organizers and Local Organizing Committee:

Michael Zemp and **Samuel Nussbaumer**, World Glacier Monitoring Service (WGMS), University of Zurich (UZH), Switzerland.

Peter Jansson, Department of Physical Geography and Quaternary Geology, Stockholm University (SU): scientific coordinator, Tarfala.

Andrew Mercer, Department of Physical Geography and Quaternary Geology, Stockholm University (SU): mass balance measurements and geodetic surveys on Storglaciären, Sweden.

Gunhild Rosqvist, Department of Physical Geography and Quaternary Geology, Stockholm University (SU): station director, Tarfala.

Guests:

Erich Heucke and **Bernhard Heucke**, Kommission für Erdmessung und Glaziologie (KEG), Abt. Glaziologie, Bayerische Akademie der Wissenschaften, Germany: service on Heucke Ice Drill.

Minutes of the workshop

The participants gathered at Kiruna airport in the afternoon of Sunday, 8th July 2012. **Gunhild Rosqvist** guided the group with a chartered bus to Nikkaluokta, a small Sami village, where a late lunch with local food was prepared. The continuation of the journey to Tarfala Research Station went on by helicopter. Thanks to perfect weather conditions, the participants could grasp marvellous views from the air of the Kebnekaise Mountains and the surrounding valleys. In the early evening, the group arrived in Tarfala and was warmly welcomed by the station staff. A welcome speech by the WGMS director Michael Zemp and by the Local Organizing Committee followed and officially opened the workshop.

Monday, 9th July 2012, started with an introductory talk by **Michael Zemp** on the workshop goals and agenda. He emphasized that the workshop aims at providing best practices for the re-analysis of glaciological and geodetic mass balance series, and quantifying the related uncertainties. In view of the increasing number of long-term mass balance series and the fact that there are several glaciers where the geodetic and glaciological results largely diverge, there is strong need to address the questions raised above. For global analyses (e.g. Kaser et al. 2006), still simple uncertainty assumptions are made. The few in-depth re-analyses (using heterogeneous approaches) show the importance of

- homogenizing both geodetic and glaciological mass balance series,
- quantifying both stochastic and systematic error uncertainties, and
- an integrative uncertainty assessment.

The resultant goals of the workshop are thus based on the following research questions:

- Which are the **sources of potential errors** of glacier mass balance measurements?
- How are these potential errors considered by **glaciological and geodetic methods**?
- How can the related uncertainties be **quantified**?

- What are typical values (ranges) for the **systematic and stochastic uncertainties**?
- What are the related consequences for the **comparison of glaciological and geodetic mass balances**?
- What are the related **consequences for the interpretation** of glacier mass balance results as indicators of climate change, fresh water resources, and contributors to sea level change?

Several input presentations followed in order to deepen the questions raised above, and to ensure the base for the workshop discussions.

Andrea Fischer made the beginning with her input presentation on the homogenization of glaciological mass balance series at Hintereisferner, Austria. The aim of homogenization of data series is to remove biases in long-term data, based on the idea adapted from time series in climatology (e.g. temperature/precipitation measurements). Biases in the series may e.g. be caused by changing instruments, location, observers, or observation times. A detected bias in the data series may be removed by the statistical analysis of time series including neighbouring stations, analysis of metadata, and the development of algorithms correcting different measurement methods. Regarding the homogenization of glacier mass balance data, the following aspects are of importance: changes in the measurement, changes in the data analysis, and changes in glacier properties (e.g. accumulation/ablation patterns). Hereby, good metadata and ideally overlapping periods of the actual observers are crucial to avoid break points in the series. Biases can be due to different maps, glacier outlines, and ways to evaluate mass balance, and interpolation of stake and pit data. As a solution, Fischer suggested finding a glacier area that allows calculating a mass balance without loss of glacier area and elevation change, and with small albedo changes (“core glacier”). Direct and geodetic glacier data seem to include different ablation processes. Hence, a combination might improve the estimate of total ablation, but at the same time it might include density changes or changes of the glacier bed for instance. More knowledge about the reasons for these deviations is needed to understand the errors of the combined product. The subsequent discussion within the plenum showed the importance of different mass balances depending on the purpose (climatological or hydrological series); as an alternative, stakes at always the same spot may replace the “core glacier” concept. The related problem of moving stakes can be solved if the stakes are measured along the same profile line.

Afterwards **Matthias Huss** gave an input talk on the re-analysis of the two long-term glaciological mass balance series at Gries- and Silvrettagletscher in Switzerland. Huss presented a method to homogenize the time series of comprehensive mass balance monitoring programmes, using a daily mass balance model. This requires seasonal mass balance data, decadal ice volume changes (geodetic data), and daily weather data. However, the question remains which one is “more correct”, the glaciological or the geodetic method. Huss discussed different components of uncertainty, for the glaciological method, as well as for the geodetic method. The re-analysis showed that in the case of Silvrettagletscher, there is big discrepancy between the two methods, which made a correction necessary. Huss concluded that a detailed analysis of all components of uncertainty for both the glaciological and geodetic method is necessary. Significant differences between systems to evaluate mass balances exist. Especially there has not yet been enough effort to quantify the error stemming from density assumptions.

Christopher Nuth then gave a key note presentation on co-registration and bias correction of elevation data. Biases occur due to slope and aspect distribution of the glacier. Nuth presented a

practical application how these biases can be detected and corrected. He showed that co-registration is simple to detect and to correct. The tool (available in Excel) presented by Nuth directly removes biases in geodetic mass balance estimates.

In the following, **Philip Joerg** gave an input talk on the uncertainty assessment of multi-temporal airborne laser-scanning data at Findelengletscher in Switzerland, obtained between 2005 and 2010. He also pointed out that in the geodetic method, the uncertainty stems mostly from density assumptions. Joerg firstly explained the principle of airborne laser-scanning and discussed related uncertainties. Besides stochastic uncertainties (higher uncertainties in steep areas including moraines), the local angle of incidence and, much more important, snow during surveys, constitute systematic uncertainties. Airborne laser-scanning is a valid and accurate data source to support glaciological research. However, uncertainties are still present on different levels, and difficult to determine. Stochastic uncertainties are negligibly small except for density estimation, and systematic uncertainties are very important.

In the afternoon, the key note presentation by **Bernhard Hynek** compared glaciological and geodetic mass balances of three small glaciers in Goldberggruppe (Hohe Tauern, Austria). Hynek presented features detected by laser-scanning methods: small glaciers with collapse effects, effects of basal melt. The setting of having three glaciers in direct neighbourhood allows for assessing the influence of local effects. Finally, the comparison with the glaciological mass balance is difficult, and the determination of uncertainties of the direct mass balance is not an easy task.

The last key note by **Emmanuel Thibert** provided a test to decide on the re-calibration of long mass balance time series. Thibert first discussed how to decide whether a mass balance series has to be re-calibrated or not. The pre-conditions are: intrinsic differences have been accounted for, random errors have been estimated/measured in the geodetic and glaciological data, identified systematic errors have been corrected. Statistics may help to decide whether a re-calibration is needed, but the decision has to be based on physical criteria. Using the example of Storglaciären, Thibert showed that due to the scattering of the data, a firm conclusion is not possible. A systematic error is hard to detect firmly. Unless running the risk of re-calibrating uselessly, the risk to keep an uncorrected series when it is actually incorrect is very high. Considering that the glaciological balance is much more sensitive to systematic error accumulations, the geodetic can be considered as an unbiased control.

After these input presentations, **Michael Zemp** presented the concept for the planned joint paper on the uncertainties in mass balance measurements. The idea of the paper (peer-reviewed) is to bring the raised issues together within a strong conceptual framework, and to give best practices and not guidelines. In this connection, three parts should be addressed: the glaciological method, the geodetic method, and the comparison of both methods. The workshop group agreed on the importance of having one common answer, as there are many papers on that topic on individual glaciers. Core of the paper is the available dataset of long-term mass balance series, and the re-calibration and homogenization of these series.

In the evening after dinner, two overview talks by **Gunhild Rosqvist** and **Peter Jansson** gave the participants a comprehensive overview of past and current research in and around the Tarfala valley, and on Storglaciären which is one of the best-studied glaciers in the world. Recent studies related to

mass balance are e.g. by Jansson (1999), Holmlund et al. (2005), Jansson and Pettersson (2007), Koblet et al. (2010), and Zemp et al. (2010).

Tuesday, 10th July 2012, brought an excursion to Storglaciären with on-site discussions of issues discussed the day before. The excursion was led by **Peter Jansson** with assistance of **Andrew Mercer**. The group safely hiked to Storglaciären (about one hour from the research station) and entered the glacier for an easy walk. Due to plenty of snow from last winter, the glacier was still nearly completely snow-covered which is rather unusual. During the walk, Peter Jansson gave valuable information on the current mass balance programme and about glacier dynamics, as well as an interpretation of the impressive moraine formations.

On Wednesday, 11th July 2012, **Michael Zemp** explained a prepared draft of the planned paper, as a joint outcome of the workshop. In line with scope of the workshop, the paper aims at identifying and quantifying the uncertainties of glaciological and geodetic mass balance measurements as well as at providing best practices for the re-analysis of mass balance series. It should entail key references, an explanation of the concepts, a clarification of the terminology, a complete list of potential error sources, and all equations needed. The majority of mass balance data series consist of just a few observation years and most results are reported without error bars. Guidelines are not yet available for the re-analysis process, and a direct comparison of recent findings is often challenging. This shows the strong need for a consensus how to tackle these issues, and to provide a strong conceptual framework. Potential errors (random and systematic) in the glaciological method are twofold: related to point measurement and related to spatial integration. In addition, the applied time system (floating, fixed, stratigraphic; northern, tropics, southern) has to be taken into account. On the other hand, potential errors in the geodetic method are due to point measurements (sighting), the integration of the point measurements (sampling), and related to spatial orientation, among others. Required for a comparison of the two methods are common time systems, reference areas, density assumptions, and it has to be accounted for the generic differences between glaciological and geodetic mass balance (i.e. surface mass balance vs. climatic-basal mass balance, cf. Cogley et al. 2011).

The proposed scheme for the re-analysis of mass balance series is as follows:

- (1) Observation
→ meta-data provide the basis for (2) and (3)
- (2) Homogenization
→ helps to reduce the systematic uncertainties
- (3) Uncertainty assessment
→ required for a direct comparison of both methods
- (4) Validation
→ definition of a confidence level for decision about re-calibration
- (5) Re-calibration
→ how to deal with the re-calibration of seasonal balances?
→ how to deal with the re-calibration of ELA and AAR values?
→ consequences for interpretation of results (climate vs. hydrological signal)

A conclusion for mass balance monitoring programmes is that early geodetic surveys are required, to be repeated about every decade.

In the following, the workshop group was split in three sub-groups to ensure best possible discussions of the available paper draft:

- Group 1 (chair: Andrea Fischer): issues concerning the glaciological method
- Group 2 (chair: Cecilie Rolstad Denby): issues concerning the geodetic method
- Group 3 (chair: Liss Andreassen): comparison of the two methods and synthesis

In the afternoon, a plenary discussion on the paper draft was held. **Andrea Fischer** presented the outcome of the sub-group discussion with focus on the glaciological method. She raised the question whether all glaciers should be treated in the same way, i.e. if it is feasible to derive one general approach for all glaciers. Measurements and processing differ from glacier to glacier. Hence, differences between the glaciological and geodetic method can result from different sources. Fischer further explained how errors (stochastic and systematic) should practically be calculated or estimated. Number and distribution of point measurements are important and the inter-/extrapolation method is specific for each glacier. Other aspects such as vertical motion, different seasons, and other hot topics were mentioned in the discussion, too. Uncertainties that are difficult to assess are the unknown representativeness of point measurements and the variability of the mass balance. Finally, precise definitions of the various terms used in the paper are needed.

Cecilie Rolstad Denby then presented the outcome of sub-group dealing with issues related to the geodetic method. Two different error sources are identified: due to stakes and due to the area. A solution is to apply more statistical methods and to add the co-registration method to correct for biases. The determination of systematic errors should be described. Regarding stochastic errors, the density assumption is considered to be the main uncertainty. Finally, there is an agreement that guidelines for geodetic measurements should be included with some references.

The sub-group presentations were completed by the overview given by **Liss Andreassen**. As major point, it was stated that the paper should not be too extensive with new analyses, but include a review what has been done so far, supplemented with recommendations. Major issues related to the glaciological method are the inter-/extrapolation and the internal accumulation. Regarding the geodetic method, the uncertainties due to density assumptions and inaccurate DEMs are determinant. Overall, it must be differentiated between alpine glaciers and ice caps. In contrast to measurements, there are no manuals for calculations and uncertainty estimates. Open questions remain, such as how to handle the correction of mass balance series (e.g. continuation of the mass balance programme after major revision, or correction for certain time periods only).

In the subsequent general discussion, there was an agreement on the publication strategy, contribution, and deadlines. In view of the consensus that direct glacier mass balance series need to be checked geodetically at regular intervals (depending on glacier changes and the quality of the geodetic assessments), the paper shall provide a decision tool to judge whether a series needs to be adjusted. In addition, recommendations shall be given how to tackle those issues, and unsolved issues are added as an outlook. The intended journal is "The Cryosphere" because its content is freely available and it allows an open discussion, incorporating feedback from the community. Extra tables and possibly an exercise for one glacier can be added in the supplementary material. After clarifying remaining questions, the workshop was officially closed. In the evening, the group once again enjoyed culinary treats (Lappish food) by the Tarfala staff, and excited discussions after dinner let the people looking back on the past workshop days.

Thursday, 12th July 2012, the weather conditions changed from good to bad, which implied that the group could not leave the station by helicopter. Instead, the group enjoyed a 2 hours walk through the impressive Tarfala valley down to Kebnekaise mountain station, where the continuation by helicopter to Nikkaluokta (20 km) was possible.

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